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# Improved detection of acute myocardial infarction using a diagnostic algorithm based on calculated epicardial potentials

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**Abstract**

*Background:* New methods for detecting myocardial infarction in patients with suspected acute coronary syndromes are needed particularly in an era where the majority of patients with myocardial infarction present with non-diagnostic 12-lead electrocardiograms (ECG). We compared a novel epicardial diagnostic algorithm using epicardial potentials from the 80-lead body surface map with other electrocardiographic techniques in detection of myocardial infarction.

*Methods:* Between February 1999 and February 2001, consecutive patients ($n=427$) with ischemic type chest pain had an initial 12-lead ECG and body surface map recorded. Detecting myocardial infarction using an epicardial algorithm was first performed in a training set ($n=213$) and tested in a validation set of patients ($n=214$). The results from this epicardial algorithm in myocardial infarction detection were compared with the physician's interpretation of the 12-lead ECG, the body surface map algorithm (PRIME™) and physician's interpretation of the body surface map.

*Results:* Myocardial infarction occurred in 205 patients (creatine kinase $\geq 2\times$ upper limit of normal with creatine kinase-MB $\geq 7\%$ CK). The physician's interpretation of the 12-lead ECG identified 122 with myocardial infarction (sensitivity 60%, specificity 99%), the body surface map algorithm 137 (sensitivity 67%, specificity 89%), the physician's interpretation of the body surface map 153 (sensitivity 75%, specificity 91%) and the epicardial algorithm 158 (sensitivity 77% specificity 99%). Combining the physician's interpretation of the 12-lead ECG with the epicardial algorithm increased significantly the detection of myocardial infarction (sensitivity 85%, specificity 98%, $p \leq 0.001$) compared with the 12-lead ECG.

*Conclusions:* An epicardial algorithm based on epicardial potentials increases significantly the detection of myocardial infarction particularly among those with non-diagnostic 12-lead ECG's.


*Keywords:* Myocardial infarction; Epicardial algorithm; Ventricular hypertrophy; Epicardial potentials

## 1. Introduction

The 12-lead electrocardiogram (ECG) is essential in the initial evaluation of a patient with suspected acute coronary syndromes. It can confer similar if not better prognostic information than troponin measurements [1]. Nevertheless, there remains the need to improve the diagnostic capability of the 12-lead ECG as it only has 50–60% sensitivity for acute myocardial infarction detection [2] as many patients present with atypical ECG changes such as ST depression, T inversion, left bundle branch block or left ventricular hypertrophy. One method which improves the diagnostic capability of the 12-lead ECG is by sampling over a larger thoracic surface such as

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the right ventricle, lateral and posterior regions—a technique known as body surface potential mapping. We have already shown that an 80-lead body surface map improves the detection of acute myocardial infarction in patients presenting with ST-elevation, ST-depression and left bundle branch block [3–5].

However, even with the body surface map there remains a significant number of myocardial infarctions that remain undetected. Surface ECGs are manifestations of electrical signals that are attenuated and smoothed by the thoracic volume conductor as they pass from the cardiac source to the body surface. Electrocardiographic imaging is a non-invasive functional imaging method for reconstructing electrophysiological information about the surface of the heart from body surface measurements and previous work has demonstrated its usefulness in the non invasive detection of arrhythmogenic pathways in ventricular tachycardia, image abnormal electrophysiological substrates associated with infarction and improvement in the detection of acute myocardial infarction [6–8]. In a previous study we used a general thoracic volume conductor model based on images obtained from the visible human viewer project [9] in order to calculate epicardial potentials. Although the use of epicardial potentials improved significantly the detection of acute myocardial infarction by a factor of 1.25, the specificity was suboptimal mainly due to the inability of the diagnostic algorithm to detect confounders such as left bundle branch block and left ventricular hypertrophy and to predict acute myocardial infarction in the presence of these [8].

The aims of this study were: (a) to improve the specificity of the diagnostic algorithm by developing rules to detect acute myocardial infarction in the presence of the confounders left ventricular hypertrophy and bundle branch block in a training set population and to test this algorithm in a validation set of patients and (b) to compare the performance of this diagnostic algorithm with a physician's interpretation of the 12-lead ECG, body surface map and a body surface map diagnostic algorithm [3] in patients with acute coronary syndromes.

## 2. Materials and methods

### 2.1. Patient recruitment

Patients were recruited consecutively between February 1999 and February 2001 as they presented via the mobile coronary care unit or emergency department. Patients were enrolled throughout the 24 h if they presented with ischaemic type chest pain of <12 h duration regardless of the presenting 12-lead ECG. All patients had a 12-lead ECG and body surface map performed at presentation together with serial cardiac enzymes (creatine kinase and creatine kinase-MB). Patients were excluded if they had pain <20 min, or had received fibrinolytic therapy, or nitrates or glycoprotein IIb/IIIa inhibitors prior to the initial 12-lead ECG or body surface map, could not give informed consent or had the body surface map >15 min after the 12-lead ECG ($n=93$).

### 2.2. Body surface map

The body surface map comprises a flexible plastic anterior and posterior electrode harness and a portable recording unit. The anterior harness contains 64 electrodes, including 3 proximal bipolar limb leads (Mason–Likar position), and a posterior harness with 16 electrodes. This lead configuration enables recording of 77 unipolar ECG signals with respect to the Wilson central terminal. During the interpretation process the electrodes are defined to represent anterior, lateral, inferior, right ventricular and posterior epicardial regions [10].

### 2.3. Data collection and analysis

Cardiac technicians recorded 12-lead ECGs and body surface maps at initial presentation. The 80-lead ECGs were uploaded and displayed on an IBM compatible computer running PRIME™ analysis software (Meridian Medical Technologies, Belfast, Northern Ireland). All 80 leads were manually checked and those of unacceptable quality (i.e. those leads where noise or movement artefact disallows

Table 1
Definitions of abnormal 12-lead ECG features

| Abnormal 12-lead ECG features | Definition |
|---|---|
| Regional ST elevation (Minnesota code 9-2) | PR segment as isoelectric reference.<br>ST elevation measured at the J point<br>Inferior STE*: ≥0.1 mV in ≥2 leads II, III, aVF<br>Lateral STE: ≥0.1 mV in ≥2 leads I, aVL, V5, V6<br>Anterior STE ≥0.2 mV in ≥2 leads V1–V4 |
| ST depression | ≥0.05 mV depression 80ms following the J-point in any lead excluding aVR |
| T inversion | T inversion ≥0.1 mV |
| Pathological Q waves | Duration ≥0.03 s or amplitude Q:R ratio ≥25% |
| Left bundle branch block | QRS duration ≥120 ms<br>QS or rS in V1 and broad slurred R waves in lead I and V5 or V6 |
| Right bundle branch block | QRS duration ≥120 ms<br>rSR′ in V1 and V2 and S waves in lead I and V5 or V6 |
| Left ventricular hypertrophy | Female: R wave aVL>1.1 mV<br>Male: R wave aVL>1.3 mV<br>(SV1+RV5 or V6)>3.8 mV. |
| Minor STT changes | <0.05 mV depression 80ms following the J-point in any lead excluding aVR<br>T inversion <0.1 mV or T wave flattening |

STE: ST-segment elevation.

recognition of QRST variables) were marked and substituted using linear grid interpolation. Maps with more than 6 'bad leads' were disregarded to avoid inappropriate reliance on interpolated data. QRS onset, offset and T wave offset for each lead were marked enabling the following variables to be calculated:

1. QRS width and axis
2. QRS and ST-T isointegrals—an integration of the ECG signal under the QRS and ST-T curves at each electrode site
3. ST0 and ST60 isopotentials—the potential at each electrode at 0 and 60 ms after the ST0 (J point).

### 2.4. Twelve-lead ECG analysis

A cardiologist blinded to the clinical details measured key elements of the QRST morphology for each patient and recorded abnormal ECG features as detailed in Table 1. ST elevation consistent with acute myocardial infarction was documented based on the Minnesota code 9-2 which requires $\geq$0.1 mV ST segment elevation in two or more of leads I, II, III, aVL, aVF, V5, V6 or $\geq$0.2 mV ST elevation in two or more of leads V1–V4 [4]. The Minnesota code criteria were used for diagnosis of acute myocardial infarction as it has been proven to be superior in determining AMI compared with other ST-elevation criteria.

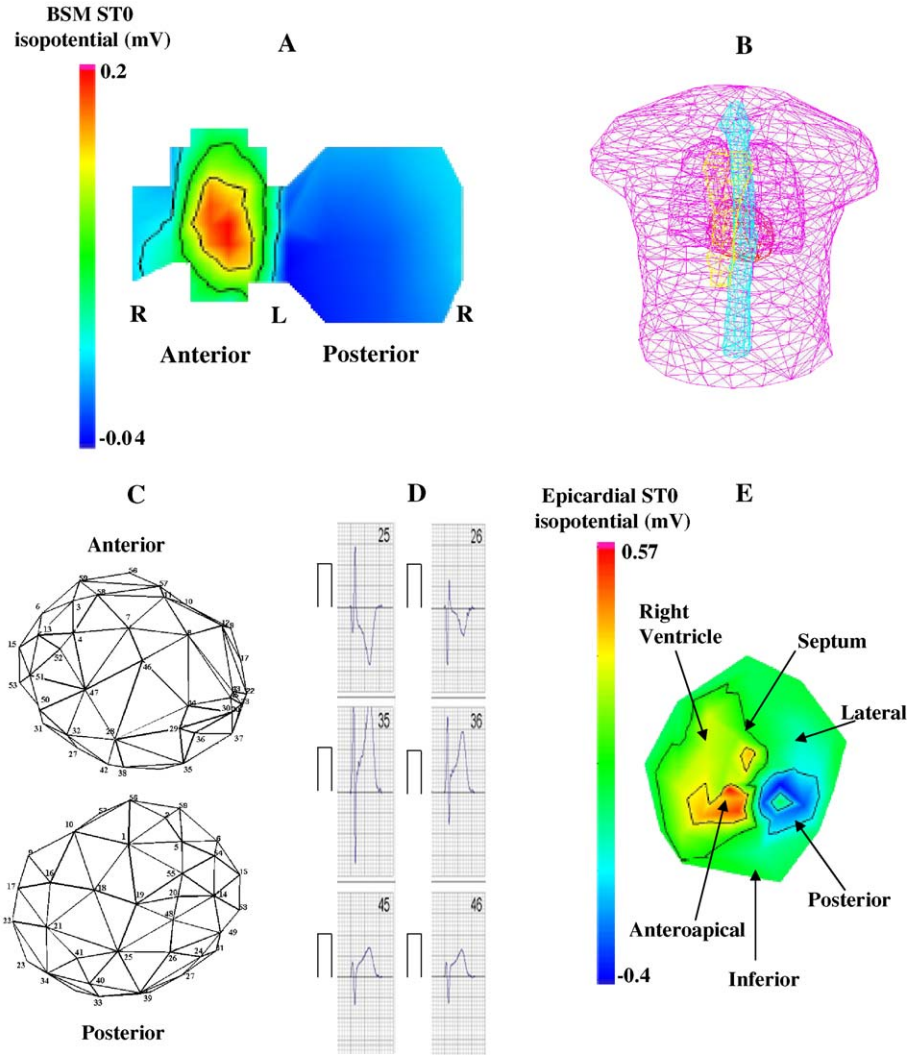


Fig. 1. Generating epicardial electrocardiograms and epicardial contour maps. (A) ST0 isopotential body surface map showing anterior maxima (0.2 mV, red) and posterior minima (−0.04 mV, blue) consistent with an acute anterior infarct. (B). Illustration of the three dimensional mesh that consists of 11,404 tetrahedral elements, 1136 torso surface nodes and 59 epicardial nodes used in the mathematical formulation of the general thoracic volume conductor model. (C) Anterior (top) and posterior (bottom) epicardial surface containing 59 virtual node positions from which epicardial electrocardiograms are produced. (D) Epicardial electrocardiogram showing epicardial ST-elevation in the nodes relating to the anterior territory (as produced with Microsoft Excel ™). The scale is 25 small squares per second on the *x* axis and 1 small square = 0.1 mV on the *y* axis. This demonstrates epicardial ST-elevation in the anterior territory. (E) ST0 epicardial polar map. In this view the whole epicardial surface is displayed on a 2-dimensional circle similar to the "bullseye" view in myocardial perfusion imaging. In this example there is an antero-apical, septal and right ventricular maxima (0.57 mV, red) with a reciprocal posterior minima (−0.4 mV, blue) consistent with an anterior infarction with right ventricular involvement. The black contour lines unite areas of equal potential.

Other QRST variables such as R/S waves have poor sensitivity at detecting posterior infarction though good specificity and precordial ST depression has both poor sensitivity and specificity [4,11].

### 2.5. Physician body surface map interpretation

A single cardiologist familiar with body surface map interpretation and blinded to the clinical details, 12-lead ECG and PRIME™ diagnostic algorithm result coded the body surface maps as acute myocardial infarction and defined the infarct location. The ST0 isopotential map was interpreted together with the 80-lead ECG to ensure the physician can view ST and QRS morphology and hence recognise left ventricular hypertrophy and bundle branch block. ST elevation was measured from the ST0 point (i.e., 0ms after the J point) with the following thresholds:

Anterior: ST elevation $\geq$0.2 mV
Lateral/inferior/right ventricular: ST elevation $\geq$0.1 mV
Posterior: ST elevation $\geq$0.05mV

### 2.6. Body surface map diagnostic algorithm

The results of the PRIME™ diagnostic algorithm were documented.

### 2.7. Acute myocardial infarction definition

Acute myocardial infacrtion was diagnosed when creatine kinase rose to at least twice the upper limit of the normal laboratory reference range with creatine–kinase–MB at least 7% of the total creatine kinase.

### 2.8. Calculation of epicardial potentials

The construction of the general thoracic volume conductor model and the mathematical formulation to calculate epicardial potentials has been described previously [8]. Epicardial potentials are derived from an epicardial model composed of 59 nodes, each of which act as virtual electrode positions from which epicardial electrocardiograms are reconstructed (Fig. 1). During the interpretation process the epicardial nodes are defined to represent anterior, septal, lateral, inferior, apical, right ventricular and posterior epicardial regions. From these epicardial electrocardiograms, standard QRST variables can be calculated [12].

### 2.9. Algorithm design

In order to derive the rules for detecting acute myocardial infarction in the presence of confounders i.e., bundle branch block, left ventricular hypertrophy, the patients were randomly divided into two groups; a training set and a validation set. In the training set, the cases were classified based on the presenting 12-lead ECG and cardiac enzymes and epicardial electrocardiographic features were then derived which best discriminated the variable being tested (i.e., left ventricular hypertrophy, bundle branch block, acute myocardial infarction). Only those features which improved significantly the performance of the diagnostic algorithm in detecting acute myocardial infarction were included. The algorithm design was intended to mirror the approach of a cardiologist and follows a stepwise decision-tree approach as shown in Fig. 2. The final algorithm (epicardial features) was then tested in the validation set.

### 2.10. Conduction delay

Conduction delay was defined as epicardial QRS duration $\geq$120 msec and bundle branch block was defined by looking at the node where activation occurs earliest. Activation times were taken when the greatest negative rate of change occurs for the QRS [13]. This method allowed the following to be defined:

1. Right Bundle Branch Block: QRS duration $\geq$120 ms and activation predominantly occurs earliest in the left ventricle and latest in the right ventricle.
2. Left Bundle Branch Block: QRS duration $\geq$120 ms and activation predominantly occurs earliest in the right ventricle and latest in the left ventricle.
3. Non specific conduction delay: QRS duration $\geq$120 ms not fitting above activation pattern [1] or [2].

### 2.11. Left bundle branch block with acute myocardial infarction

The following criteria were found to be useful in detecting acute myocardial infarction in the presence of left bundle branch block using the following sequence:

1. Change of angle from QRS isointegral to STT isointegral vectors outside 180±20° [5] or
2. The ratio of the epicardial ST0 maxima (mV) to the maximal R wave amplitude (mV) in the corresponding concordant QRS complex >0.25 or
3. The ratio of the ST0 maxima (mV) to the maximal R wave amplitude (mV) in the corresponding biphasic QRS complex >0.6.

### 2.12. Right bundle branch block with acute myocardial infarction

The following criteria were found to be useful in detecting acute myocardial infarction in the presence of right bundle branch block:

1. ST0 maxima >0.9 mV or
2. The ratio of the ST0 maxima (mV) to the maximal R wave amplitude (mV) in the corresponding concordant QRS complex >0.2 or

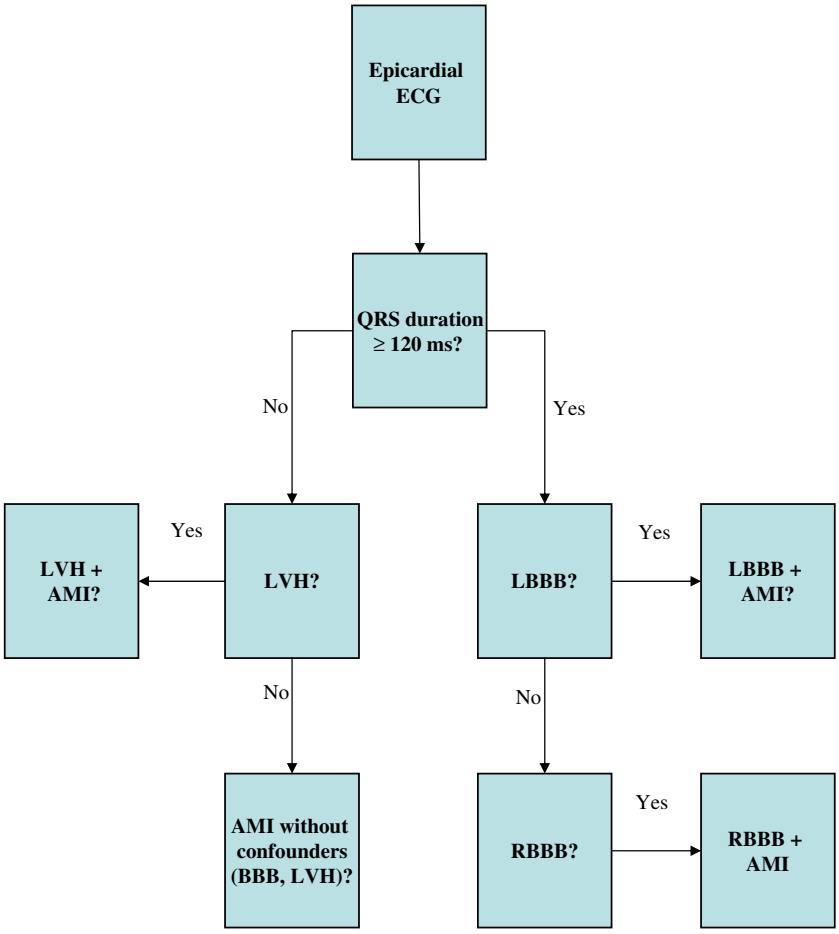


Fig. 2. Flow diagram for the epicardial diagnostic algorithm. LBBB: left Bundle Branch Block. RBBB: Right Bundle Branch Block. LVH: Left Ventricular Hypertrophy. AMI: Acute Myocardial Infarction. BBB: Bundle Branch Block. ECG: electrocardiogram.

3. The ratio of the ST0 maxima (mV) to the maximal R wave amplitude (mV) in a corresponding biphasic QRS complex >0.12.

*2.13. Left ventricular hypertrophy*

1. Mean R wave nodes1–7>5.4 mV or
2. Mean R wave in apical nodes >7.1 mV *and* maximum apical R wave (mV)-mean apical R wave (mV) <1.0mV or
3. If any apical R wave >10.0 mV *and* mean left ventricular R wave >3 mV or
4. Septal S waves >3.1 mV.

*2.14. Left ventricular hypertrophy with acute myocardial infarction*

1. Vector magnitude (ST0 maxima–ST0 minima) >1.5 mV and 2 the ration of STO maxima

1. The ratio of ST0 maxima to the tallest R wave in any node >0.07.

*2.15. Acute myocardial infarction not complicated by confounders*

Acute myocardial infarction was detected in the absence of confounders by the following definitions

1. Vector magnitude (ST0 maxima–ST0 minima) >1.2 mV or
2. ST0 maxima >0.3 mV *and* ST0 minima >0.3 mV.

## 3. Statistical analysis

Baseline categorical variables were analysed by chi-square and continuous clinical variables by analysis of variance. Sensitivity and specificity of the various diagnostic methods were calculated by comparing the prediction of acute myocardial infarction against the cardiac enzymes. Overall performance of the various diagnostic methods was by ROC curve analysis with area under the curve (c-statistic) >0.75 taken as good performance. McNemar's test was used to compare the epicardial algorithm's prediction of

Table 2
Demographics, risk factors for ischemic heart disease, creatine kinase and fibrinolytic therapy for training and validation set patients

| | Training set $n=213$ | Validation set $n=214$ |
|---|---|---|
| Mean Age (±SD) | 61±13 | 62±12 |
| Male | 166 (78%) | 156 (73%) |
| Current smoker | 124 (58%) | 123 (58%) |
| Hypertension | 90 (42%) | 94 (44%) |
| Hypercholesterolemia* | 124 (58%) | 116 (54%) |
| Family history of ischemic heart disease | 141 (66%) | 133 (62%) |
| Diabetes mellitus | 30 (14%) | 28 (13%) |
| Mean creatine kinase (±SD) | 914 (±1593) | 799 (±1250) |
| Fibrinolytic therapy | 71 (33%) | 60 (28%) |

SD: Standard Deviation.
* Defined as total cholesterol >5 mmol/L.

acute myocardial infarction with either of the 12-lead ECG, body surface map algorithm and physician's body surface map interpretation. Statistical analysis was performed using SPSS version 10.0 (SPSS Inc, Chicago, Illinois). A $p$-value $<0.05$ was taken as statistically significant. The study was approved by the Queen's University Belfast Research Ethics Committee. All patients gave informed consent.

## 4. Results

Four hundred and twenty seven patients were recruited. Based on cardiac enzymes, 205/427 (48%) had acute myocardial infarction. Acute myocardial infarction occurred in 107/213 (50%) in the training set and 98/214 (46%) in the validation set. Training and validation sets were comparable with no significant differences between sets with respect to baseline demographics, risk factors for ischaemic heart disease, mean creatine kinase, treatment by fibrinolytic therapy and acute myocardial infarction distribution (Tables 2 and 3). The cases were classified according to the most dominant feature on the 12-lead ECG with ST-elevation of primary importance followed by left bundle branch block, right bundle branch block, left ventricular hypertrophy, ST-depression (in the absence of ST-elevation), T-inversion, Q-waves, minor STT changes and normal ECG's (Table 3). There were no significant differences between sets with respect to ECG classification (Table 3).

### 4.1. Physician interpretation of the 12-lead ECG

Based on Minnesota criteria for ST-segment elevation, the physician correctly identified 62/107 patients with acute myocardial infarction in the training set (58% sensitivity, 99% specificity), 60/98 patients with acute myocardial infarction in the validation set (61% sensitivity, 99% specificity) (Table 4). Thus the physician correctly identified 122/205 patients with acute myocardial infarction in the total group (sensitivity 60%, specificity 99%, c-statistic 0.79) (Table 4). Based on cardiac enzymes and locality of ST-elevation, 38 (31%) were classified as anterior ST-elevation acute myocardial infarction, 76 (62%) as inferior ST-elevation acute myocardial infarction and 8 (7%) as lateral ST-elevation acute myocardial infarction.

### 4.2. Body surface map algorithm

The PRIME™ body surface map algorithm correctly identified 71/107 patients with acute myocardial infarction in the training set (sensitivity 66%, specificity 92%), 66/98 patients with acute myocardial infarction in the validation set (sensitivity 67%, specificity 86%). Thus the body surface map algorithm identified 137/205 patients with acute myocardial infarction in the total group (sensitivity 67%, specificity 89%, c-statistic 0.78). There was no significant difference between the 12-lead and body surface

Table 3
12-lead ECG features for AMI-compared with non-AMI in training and validation sets

| | Training set (n=213) | | Validation set (n=214) | | $p$ |
|---|---|---|---|---|---|
| ECG Classification | AMI [a] $n=107$ | Non-AMI $n=106$ | AMI $n=98$ | Non-AMI $n=116$ | |
| Anterior STE[b] | 17 | 0 | 21 | 1 | NS |
| Inferior STE | 42 | 0 | 34 | 0 | NS |
| Lateral STE | 4 | 1 | 4 | 0 | NS |
| Left bundle branch block | 1 | 4 | 3 | 7 | NS |
| Right bundle branch block | 1 | 5 | 1 | 6 | NS |
| Left ventricular hypertrophy | 4 | 14 | 1 | 10 | NS |
| ST-depression | 14 | 6 | 10 | 3 | NS |
| T-inversion | 4 | 19 | 5 | 16 | NS |
| Q waves | | | | | |
| Anterior | 4 | 5 | 10 | 12 | NS |
| Inferior | 12 | 6 | 5 | 8 | NS |
| Lateral | 0 | 0 | 0 | 1 | NS |
| Minor STT changes | 3 | 6 | 3 | 8 | NS |
| Normal | 1 | 40 | 1 | 44 | NS |

[a] AMI=Acute myocardial infarction.
[b] STE=ST elevation.

Table 4
Different diagnostic methods for detecting acute myocardial infarction in training set, validation set and total group

| | Training set $n=213$ AMI $n=107$ Non-AMI $n=106$ | | Validation set $n=214$ AMI $n=98$ Non-AMI $n=116$ | | Total $n=427$ AMI $n=205$ Non-AMI $n=222$ | | Negative predictive value $n=427$ | Positive predictive value $n=427$ | c-statistic (Area under the curve) $n=427$ |
|---|---|---|---|---|---|---|---|---|---|
| | Sens % | Spec % | Sens % | Spec % | Sens % | Spec % | % | % | |
| 12-lead ECG | 58 | 99 | 61 | 99 | 60 | 99 | 73 | 99 | 0.79 |
| BSM (algorithm) | 66 | 92 | 67 | 86 | 67 | 89 | 77 | 89 | 0.78 |
| BSM (Physician) | 70 | 92 | 80 | 91 | 75 | 91 | 81 | 92 | 0.83 |
| Epicardial algorithm[a] | 72 | 81 | 77 | 78 | 74 | 79 | 80 | 82 | 0.77 |
| Epicardial algorithm[b] | 78 | 99 | 77 | 99 | 77 | 99 | 83 | 99 | 0.88 |
| 12-lead ECG+ epicardial algorithm[b] | 86 | 98 | 85 | 98 | 85 | 98 | 88 | 98 | 0.91 |

[a]: Epicardial algorithm, unadjusted for confounders [b]: Epicardial algorithm, adjusted for confounders AMI: acute myocardial infarction Sens: sensitivity Spec: specificity. BSM: Body surface map.

map algorithm at detecting acute myocardial infarction ($p=0.063$).

### 4.3. Physician interpretation of the body surface map

Using the body surface map, the physician correctly identified 75/107 patients with acute myocardial infarction in the training set (sensitivity 70%, specificity 92%), 78/98 patients with acute myocardial infarction in the validation set (sensitivity 80%, specificity 91%). Thus the physician's interpretation of the body surface map correctly identified 153/205 patients with acute myocardial infarction in the total group (sensitivity 75%, specificity 91%, c-statistic 0.83). Compared with the 12-lead ECG, the body surface map significantly increased the detection of acute myocardial infarction by a factor of 1.25 (122/205 vs 153/205, $p<0.001$).

### 4.4. Epicardial algorithm

The epicardial algorithm, unadjusted for detection of confounders correctly identified 77/107 patients with acute myocardial infarction in the training set (sensitivity 72%, specificity 81%), 75/98 patients with acute myocardial infarction in the validation set (sensitivity 77%, specificity 78%). Thus this epicardial algorithm correctly identified 152/205 patients with acute myocardial infarction though with poor specificity (sensitivity 74%, specificity 79%, c-statistic 0.77). The epicardial algorithm, adjusted for detection of the confounders left ventricular hypertrophy and bundle branch block and acute myocardial infarction in the presence of these, correctly identified 83/107 patients with acute myocardial infarction in the training set (sensitivity 78%, specificity 99%), 75/98 patients with acute myocardial infarction in the validation set (sensitivity 77%, specificity 99%) and thus overall 158/205 patients with acute myocardial infarction with markedly improved specificity (sensitivity 77%, specificity 99%, c-statistic 0.88) (Table 4). Comparing the two epicardial algorithms, although there was no significant differences between the two algorithms for detecting acute myocardial infarction ($p=0.377$), the differences in confirming the detection of no-acute myocardial infarction (i.e., specificity) was significant ($p<0.001$). The epicardial algorithm adjusted for confounders, significantly improved the detection of acute myocardial infarction compared with the 12-lead ECG by a factor of 1.3 whilst maintaining specificity (122/205 vs 158/205, $p<0.001$).

Combining the physician's interpretation of the 12-lead ECG with the epicardial diagnostic algorithm (adjusted for confounders) significantly improved the detection of acute myocardial infarction with no significant loss in specificity compared with the 12-lead ECG: in the training set this combination correctly identified 92/107 patients with acute myocardial infarction (sensitivity 86%, specificity 98%) and 83/98 patients with acute myocardial infarction in the validation set (sensitivity 85%, specificity 98%), thus correctly identifying 175/205 patients with acute myocardial infarction in the overall group (sensitivity 85%, specificity 98% $p<0.001$).

## 5. Discussion

There have been major advances in the diagnosis and risk stratification of patients with suspected acute coronary syndromes. The current markers of myocardial necrosis are highly sensitive and specific but do not reliably increase until 12 h post symptom onset which may lead to potential delays in definitive treatment [14]. Echocardiography, radionuclide imaging and even magnetic resonance imaging have all added value in acute coronary syndrome patients particularly those with non-diagnostic ECG's [15–17] but are not available routinely to all departments particularly in emergency departments where these patients are often first triaged or outside hospital when seen by the pre-hospital units.

Thus the 12-lead ECG still remains the gold standard in the immediate triage and infarct recognition of patients with suspected acute coronary syndromes. However this technology has lagged behind relative to other diagnostic methods as described. In this study we demonstrate the clinical utility of a novel electrocardiographic method at assessing patients with acute coronary syndromes and show

that a diagnostic algorithm based on epicardial potentials is comparable to a physician interpreting the BSM and superior to a physician interpreting the 12-lead ECG. This is in agreement with previous studies which have demonstrated the effectiveness of diagnostic algorithms in improving acute myocardial infarction detection but do so by complex regression algorithms or neural network techniques [3,18,19]. In contrast with these algorithms, the epicardial algorithm mirrors the diagnostic approach of a cardiologist and its rules are based on accepted electrocardiographic principles. In the left bundle branch block criteria, change in vector angle has been previously described and reflects the spatial relationship between depolarisation and repolarisation vectors and use of ST-elevation in left bundle branch block has been well described by Eriksson et al. and Shiplak et al. [5]. The left ventricular hypertrophy detection criteria are based on the most characteristic finding of increased amplitude of the QRS complex particularly in leads facing the left ventricular apex (V5, V6) and deep S waves in right ventricular leads (that is, V1 and V2) [20].

The main improvement in acute myocardial infarction detection by the epicardial algorithm was in patients with non-diagnostic changes on the 12-lead ECG: 83/205 (40%) of patients were classified as non-ST elevation acute myocardial infarction (Tables 3 and 5). In this group, of the 15 patients with left bundle branch block the epicardial algorithm correctly identified acute myocardial infarction in the 4 with acute myocardial infarction (100% sensitivity, 100% specificity); of the 29 with left ventricular hypertrophy, 3 out of 5 with acute myocardial infarction (60% sensitivity, 92% specificity) and of the 33 with ST-depression, 17 out of 24 with acute myocardial infarction (71% sensitivity, 100% specificity) (Fig. 3). Compared to the other electrocardiographic techniques, the epicardial algorithm correctly identifies 53/83 non-ST elevation acute myocardial infarction patients as acute myocardial infarction (sensitivity 64%, specificity 99%) compared with 40/83 for physician interpretation of the body surface map (sensitivity 48%, specificity 91%) and 36/83 for the body surface map algorithm (sensitivity 43%, specificity 89%). This highlights the effectiveness of this algorithm in non-ST elevation acute myocardial infarction and is particularly important in an era where 70% of patients with myocardial infarction are now presenting with non diagnostic changes on the ECG [21].

However, despite the overall improvement in acute myocardial infarction detection by the epicardial algorithm (adjusted for confounders), there remained 17 cases with ST-segment elevation on the initial 12-lead ECG not detected as acute myocardial infarction by the epicardial algorithm (Table 5). There are several possible explanations for this. A significant proportion of patients were recruited pre-hospital where ECG changes are dynamic. Only a 15-min window was allowed between recording the 12-lead ECG and recording the body surface map during which the ECG findings may have altered. Whilst every effort was taken to exclude patients who received fibrinolytic therapy, other medications such as opiate analgesics may alter the ST-segment changes during this short time period. The body surface map bipolar leads, unlike the standard 12-lead ECG, are in the proximal Mason–Likar positions which may lead to discrepancy between the ECG and body surface map and thus the epicardial electrocardiograms from which epicardial potentials are derived. This modified position may also lead to a greater susceptibility to interference from skeletal muscle electrical activity which then translates into errors in the mathematical formulation of epicardial potentials.

Nevertheless in routine clinical practice the 12-lead ECG would be used in conjunction with the epicardial algorithm. It is unlikely therefore that these cases would be missed. Furthermore, we feel the clinical utility of the epicardial

Table 5
12-lead ECG features for acute myocardial infarction and the various electrocardiographic methods

| 12-lead ECG features | 12-lead ECG[a] | BSM algorithm | Physician interpretation of BSM | Epicardial algorithm[b] | 12-lead ECG+epicardial algorithm[b] |
|---|---|---|---|---|---|
| Anterior STE | 38 | 34 | 35 | 35 | 38 |
| Inferior STE | 76 | 61 | 72 | 65 | 76 |
| Lateral STE | 8 | 6 | 6 | 5 | 8 |
| LBBB | – | 3 | 2 | 4 | 4 |
| RBBB | – | 2 | 1 | 2 | 2 |
| Left ventricular hypertrophy | – | 2 | 2 | 3 | 3 |
| ST-depression | – | 13 | 13 | 17 | 17 |
| T-inversion | – | 1 | 5 | 3 | 3 |
| Q waves | | | | | |
| Anterior | – | 4 | 5 | 9 | 9 |
| Inferior | – | 7 | 8 | 12 | 12 |
| Lateral | – | 0 | 0 | 0 | 0 |
| Minor STT changes | – | 3 | 3 | 3 | 3 |
| Normal | – | 1 | 1 | 0 | 0 |
| *Total* | 122 | 137 | 153 | 158 | 175 |

BSM: Body surface map.
[a] Only by ST-elevation (Minnesota criteria).
[b] Epicardial algorithm, adjusted for confounders STE: ST-segment elevation.

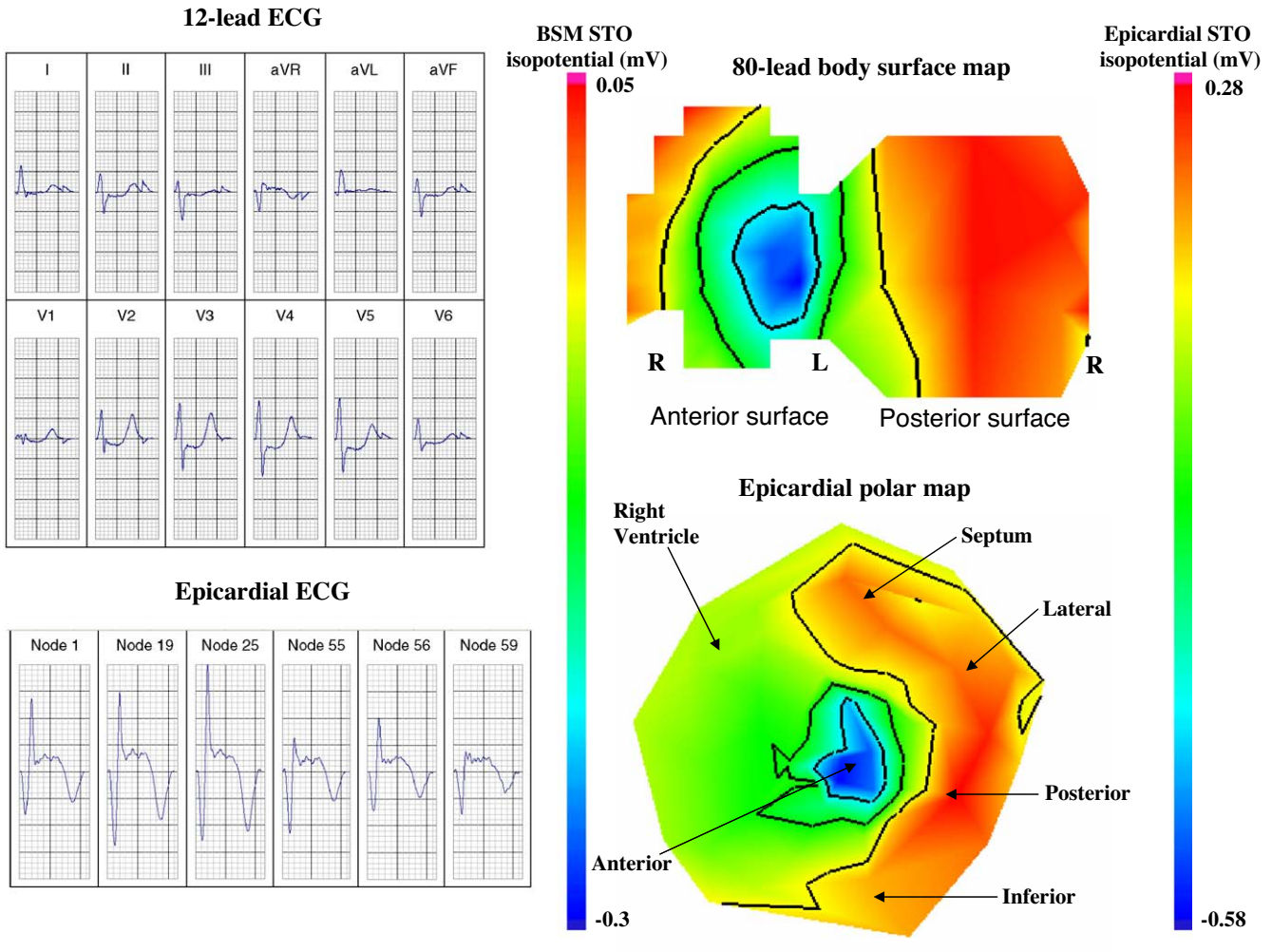


Fig. 3. 12-lead ECG (top left) of a patient with a non ST-elevation acute myocardial infarction with ST-segment depression. Corresponding 80-lead ST0 isopotential map with scale on the left showing a posterior maxima (0.05 mV, red) with a reciprocal anterior minima (−0.3 mV, blue) consistent with an acute posterior infarct. Corresponding ST0 epicardial polar map (bottom right) showing a posterior and lateral maxima (0.28 mV, red) with a reciprocal minima at the apex (−0.58 mV, blue) consistent with an acute postero-lateral infarct. The epicardial electrocardiogram from the posterior and lateral territory demonstrating epicardial ST-elevation (bottom left).

algorithm will be for those patients with non-diagnostic ECGs and thus the combination of the two diagnostic modalities would improve significantly the overall sensitivity of the 12-lead ECG. As shown in Table 4, the overall negative and positive predictive values of this approach in the population tested was 88% and 98%, respectively.

## 6. Limitations of the study

The main limitation of this study is the usage of the general thoracic volume conductor model which assigns the same chest and heart geometry to calculate epicardial potentials for all patients. This model is neither gender specific, nor takes into account variations in body shape, size or different geometrical positions of the heart. Unlike previous studies which can correlate their reconstructed epicardial potentials by using epicardial socks or multielectrode probes in canine models [6,7,22], we cannot in the clinical setting of the closed chest obtain these direct measurements. Further work is necessary to create gender specific models and to incorporate body size, weight and height into our calculations. As cardiac troponin-I or T was not available at commencement of the study and only became available routinely at the end of the study period, we plan to further test the epicardial algorithm in a larger cohort of patients with cardiac troponin data to enable a more robust test of the algorithm particularly in those patients with left bundle branch block, left ventricular hypertrophy and ST-depression.

## 7. Conclusions

Considering the increasing number of patients with acute coronary syndromes who have non-diagnostic 12-lead

ECGs, it is important to continue to evolve new electrocardiographic techniques for the rapid diagnosis and hence treatment of patients with acute coronary syndromes. We have presented a novel electrocardiographic method which, when combined with the standard 12-lead ECG, improves significantly the ability to detect acute myocardial infarction particularly in these high risk patients thus allowing their early identification and appropriate management.

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